

Course Title: Radiological Control Technician
Module Title: Radioactivity & Radioactive Decay
Module Number: 1.06

Objectives:

- 1.06.01 Identify how the neutron to proton ratio is related to nuclear stability.
- 1.06.02 Identify the definition for the following terms:
 - a. radioactivity
 - b. radioactive decay
- 1.06.03 Identify the characteristics of alpha, beta, and gamma radiations.
- 1.06.04 Given simple equations identify the following radioactive decay modes:
 - a. alpha decay
 - b. beta decay
 - c. positron decay
 - d. electron capture
- 1.06.05 Identify two aspects associated with the decay of a radioactive nuclide.
- 1.06.06 Identify differences between natural and artificial radioactivity.
- 1.06.07 Identify why fission products are unstable.
- 1.06.08 Identify the three naturally-occurring radioactive families and end product of each.
- 1.06.09 Given a nuclide, locate its block on the Chart of the Nuclides and identify the following for that nuclide:
 - a. atomic number
 - b. atomic mass
 - c. natural percent abundance
 - d. stability
 - e. half-life
 - f. types and energies of radioactive emissions
- 1.06.10 Given the Chart of Nuclides, trace the decay of a radioactive nuclide and identify the stable end-product.
- 1.06.11 Identify the definition of the following units:
 - a. curie
 - b. becquerel
- 1.06.12 Identify the definition of specific activity.
- 1.06.13 Identify the definition of half-life.

- 1.06.14 Calculate activity, time of decay, and radiological half life using the formula for radioactive decay.
- 1.06.15 Identify the definition of the following:
- a. exposure
 - b. absorbed dose
 - c. dose equivalent
 - d. quality factor
- 1.06.16 Identify the definition of the following units:
- a. roentgen
 - b. rad/gray
 - c. rem/sievert

References:

1. "Training Publication 89n, Training Publication 30n"; GPO Division of Radiological Health.
2. "Radiation Protection"; Shapiro, Jacob; Harvard University Press, Cambridge, Mass.; 1972.
3. ANL-88-26 (1988) "Operational Health Physics Training"; Moe, Harold; Argonne National Laboratory, Chicago.
4. "Basic Radiation Protection Technology"; Gollnick, Daniel; Pacific Radiation Press; 1994.
5. "Radiological Health Handbook"; Bureau of Radiological Health; U. S. Department of Health, Education, and Welfare; Washington, D.C.; 1992.
6. "Nuclides and Isotopes"; Fourteenth Edition, General Electric Company; 1989.
7. DOE/HDBK-1019 (January 1993) "Nuclear Physics and Reactor Theory" Volume 1 of 2; DOE Fundamentals Handbook Series.

Instructional Aids:

1. Overheads
2. Overhead projector/screen
3. Chalkboard/whiteboard
4. Lessons learned

I. MODULE INTRODUCTION**A. Self-Introduction**

1. Name
2. Phone Number
3. Background
4. Emergency procedure review

B. Motivation

Atoms consist of protons, neutrons, and electrons and only certain combinations of protons and neutrons exist in nature. Specific combinations of protons and neutrons within the nucleus determine whether nuclei are stable or unstable. Stable nuclei have no excess energy, while unstable nuclei, due to their surplus energy, transform themselves into stable nuclei by giving up energy. The emission of this extra energy to achieve stability is the phenomenon of *radioactivity*.

C. Overview of Lesson

1. Neutron to proton ratio
2. Radioactivity and radioactive decay
3. Radiation characteristics
4. Decay modes
5. Natural/artificial radioactivity
6. Fission product stability
7. Chart of the nuclides
8. Units of activity
9. Activity calculation
10. Measurement terminology

D. Introduce Objectives

O.H.: Objectives

II. MODULE OUTLINE**A. Nuclear Stability**

Objective 1.06.01

1. Forces in the Nucleus

See Table 1 - "Forces Acting in the Nucleus"

- a. Gravitational Force: very weak attractive force between all nucleons; acts over a relatively long range.
- b. Electrostatic Force: a strong repulsive force between like charged particles (protons); acts over a relatively long range.
- c. Nuclear Force: a strong attractive force between all nucleons; acts over an extremely short range.
- d. In stable atoms the attractive and repulsive forces balance (are equal). If forces are not balanced the nucleus will be unstable.

2. Neutron/Proton Ratio

- a. Only certain combinations or ratios of neutrons and protons will result in a balance of these forces (stable).
- b. For atomic numbers less than 20, the neutron to proton ratio (n:p) is about 1:1.
- c. As number of protons is increased, the electrostatic force increases. The numbers of neutrons must increase more rapidly in order for the nuclear force to balance with electrostatic force.
- d. As Z increases above 20 the n:p ratio gradually increases until $Z = 83$, where stable ratio is about 1.5:1.
- e. There are no completely stable nuclei with $Z > 83$.
- f. By graphing the numbers of neutrons against the number of protons for stable isotopes, a "line of stability" is depicted.

See Fig.1 - "Neutron:Proton Ratios for Stable Nuclides"

3. Stability Ranges

- a. Nuclear stability is governed by the particular combination of neutrons and protons in a given nucleus.

- b. Because many elements have several stable isotopes, there is a range for numbers of neutrons that will be stable in a nucleus with a certain number of protons.
- c. A nuclear arrangement outside of this range will be unstable. An unstable nucleus will attempt to become stable by changing its nuclear configuration.
- d. Nuclear configuration is changed by eliminating excess neutrons or protons, thereby changing the n:p ratio becoming more stable.

B. Radioactivity

Objective 1.06.02

1. Definitions

- a. Nuclear configuration changes occur through transformations. This is done by changing neutrons to protons, or vice versa and then ejecting the surplus mass or energy from the nucleus.
- b. Particles or energy emitted from the nucleus is called radiation. Radiation can be in the form of particles or waves.
- c. The property of certain radionuclides to spontaneously emit radiation is called radioactivity. In other words, if a nuclide has this property it is said to be radioactive.
- d. The emission of a particle or electromagnetic radiation in order to reach a more stable configuration produces a change or transformation.
- e. Following a transformation the nucleus is usually more stable than it was, but it may not be completely stable. So, another transformation will take place in which the nucleus will again emit radiation.
- f. The amount of energy given off and the type of emission that occurs will depend on the configuration of the nucleus immediately before a specific transformation occurs. Each step in the series of transformations will mean a distinct reduction in total mass-energy of the nucleus.
- g. As the energy of the nucleus is reduced, the nucleus is said to disintegrate or decay. The process by which a nucleus spontaneously disintegrates (or is

The term radionuclide has been coined to refer to these "radioactive nuclides."

transformed) by one or more discrete energy steps until a stable state is reached is called radioactive decay.

- h. The nucleus before the decay (or transformation) is called the parent and the nucleus after the decay is called the daughter.
- i. When there are a series of transformations before a stable state is reached, the daughter of one decay may also be radioactive and thus be the parent to another daughter.
- j. As the various steps from parent to daughter are traced to stability, a series of transmutations is seen, called a decay chain. The complete chain includes the original parent, all of its daughters and the final, stable end-product.

2. Nature of Radioactivity

- a. Certain nuclides are unstable as they occur in nature and are therefore referred to as being naturally radioactive, while others are artificially radioactive because they have become radioactive as a result of some man-made reaction.
- b. Evidence of natural radioactivity was first reported by Henri Becquerel in 1896. Becquerel demonstrated that uranium ore would darken a photographic plate shielded with opaque paper in much the same manner as X-rays. He postulated that the uranium emitted very penetrating rays, similar to X-rays.
- c. The phenomenon ultimately was called radioactivity. In time, it was determined that there were many elements beyond the atomic number of lead ($Z=82$) which showed similar radiating characteristics.
- d. After a long and complicated series of investigations, to which many outstanding physicists contributed, a better understanding of natural radioactivity was available.
- e. The understanding culminated with the experiments of Ernest Rutherford. In 1903, he clearly showed there were three kinds of radioactive emissions, which he named alpha, beta, and gamma, after the first three letters of the Greek alphabet.

C. Modes of Decay and Types of Radioactive Emissions

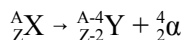
Objective 1.06.03

1. As mentioned above, Rutherford was initially able to identify three types of radiation resulting from radioactive decay: alpha, beta and gamma. Initially, all three radiations were commonly referred to as rays.
2. With time, the characteristics of each of these radiations was determined. It was found that alpha and beta are actually particulate radiations, not rays. Since then, other radiations have been discovered through numerous experiments and tests.
3. When a radioactive nuclide decays, a transmutation occurs. The decay product, or daughter has become an atom of a new element with chemical properties entirely unlike the original parent atom. With each transmutation an emission from the nucleus occurs. There are several modes of decay and emissions associated with each mode.

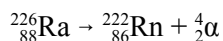
4. Alpha Decay

Objective 1.06.04 a.

- a. With a few exceptions, only relatively heavy radioactive nuclides decay by alpha emission.
- b. An alpha particle is essentially a helium nucleus. It consists of two protons and two neutrons, giving it a mass of 4 amu.
- c. Because of the two protons it has an electric charge of +2.
- d. The symbol α is used to designate alpha particles.
- e. A nucleus emitting an alpha particle decays to a daughter element, reduced in atomic number (Z) by 2 and reduced in mass number (A) by 4. The standard notation for alpha decay is:



- f. For example, Radium-226 decays by alpha emission to produce Radon-222 as follows:



- g. Alpha particles are the least penetrating of the three types of radiation. They can be absorbed or stopped by a few centimeters of air or a sheet of paper.

5. Beta Decay

Objective 1.06.04 b.

- a. A nuclide that has an excess number of neutrons (i.e. the n:p ratio is high) will usually decay by beta emission. The intranuclear effect would be the changing of a neutron into a proton, thereby decreasing the n:p ratio, resulting in the emission of a beta particle.
- b. Beta particles are negatively charged particles. They have the same mass as an electron (1/1836 of proton or 5.49E-4 amu) as well as the same charge (-1) and can be considered high speed electrons.
- c. Because of the negative charge of the beta particle, beta emission is often more explicitly referred to as "beta-minus" emission (the particle sometimes being referred to as a negatron).
- d. Beta particles originate in the nucleus, in contrast with ordinary electrons, which exist in orbits around the nucleus.
- e. The symbol β^- is used to designate beta particles.
- f. In beta-minus emitters, the nucleus of the parent gives off a negatively charged particle, resulting in a daughter more positive by one unit of charge. Because a neutron has been replaced by a proton, the atomic number increases by one, but the mass number is unchanged.
- g. In order to conserve energy and momentum between the parent and the daughter plus beta particle there is also the emission of an antineutrino, symbolized by the Greek letter nu with a bar above it ($\bar{\nu}$).
- h. The standard notation for beta decay is:



- i. For example, Lead-210 decays by beta-minus emission to produce Bismuth-210 as follows:



- j. Beta particles are emitted with kinetic energies ranging up to the maximum value of the decay energy, E_{max} . The average energy of beta particles is about $\frac{1}{3} E_{\text{max}}$.

- k. They travel several hundred times the distance of alpha particles in air and require a few millimeters of aluminum to stop them.

- l. Neutrinos (ν) and anti-neutrinos ($\bar{\nu}$) are neutral (uncharged) particles with negligible rest mass, travel at the speed of light and are very non-interacting. They account for the energy distribution among positrons and beta particles from given radionuclides in the positron- and beta-decay processes respectively.

6. Positron Decay

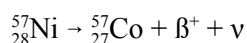
Objective 1.06.04 c.

- a. A nuclide that has a low n:p ratio (too many protons) will tend to decay by positron emission.
- b. A positron is often mistakenly thought of as a positive electron. If positive electrons existed, then when they encountered an ordinary negative electron, the Coulomb force would cause the two particles to accelerate toward each other. They would collide and then the two equal but opposite charges would mutually cancel. This would leave two neutral electrons.
- c. Actually, a positron is the anti-particle of an electron. This means that it has the opposite charge (+1) of an electron (or beta particle). Thus, the positron is a positively charged, high-speed particle which originates in the nucleus.
- d. Because of its positive charge and a rest mass equal to that of a beta particle, a positron is sometimes referred to as "beta-plus."
- e. The symbol β^{+} is used to designate positrons.
- f. With positron emitters, the parent nucleus changes a proton into a neutron and gives off a positively charged particle.

- g. This results in a daughter less positive by one unit of charge. Because a proton has been replaced by a neutron, the atomic number decreases by one and the mass number remains unchanged.
- h. The emission of a neutrino (symbolized by ν) also occurs in conjunction with the positron emission.
- i. Positron decay is illustrated by the following notation:

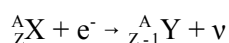


- j. For example, Nickel-57 decays by positron emission:



7. Electron Capture

- a. For radionuclides having a low n:p ratio, another mode of decay can occur known as orbital electron capture (EC).
- b. In this radioactive decay process the nucleus captures an electron from an orbital shell of the atom, usually the K shell, since the electrons in that shell are closest to the nucleus. This mode of decay is frequently referred to as K-capture.
- c. The transmutation resembles that of positron emission, as follows:

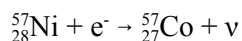


- d. The electron combines with a proton to form a neutron, followed by the emission of a neutrino.
- e. Electrons from higher energy levels immediately move in to fill the vacancies left in the inner, lower-energy shells. The excess energy emitted in these moves results in a cascade of characteristic X-ray photons.
- f. Either positron emission or electron capture can be expected in nuclides with a low n:p ratio.
- g. The intranuclear effect of either mode of decay would be to change a proton into a neutron, thus increasing the n:p ratio.

Objective 1.06.04 d.

The nucleus might conceivably capture an L-shell electron, but K-electron capture is much more probable.

- h. Note that ^{57}Ni has two modes of decay. This is an example of branching which is explained in the section DECAY PHENOMENA.



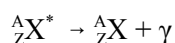
8. Gamma Emission

- a. Gamma emission is another type of radioactive decay. Nuclear decay reactions resulting in a transmutation generally leave the resultant nucleus in an excited state. Nuclei, thus excited, may reach an unexcited or ground state by emission of a gamma ray.
- b. Gamma rays are a type of electromagnetic radiation. They behave as small bundles or packets of energy, called photons, and travel at the speed of light.

For all intents and purposes, gamma radiation is the same as X-rays. Gamma rays are usually of higher energy (MeV), whereas X-rays are usually in the keV range. The basic difference between gamma rays and X-rays is their origin; gamma rays are emitted from the nucleus of unstable atoms, while X-rays originate in the electron shells.

The basic difference between gamma rays and visible light is their frequency.

- c. The symbol γ is used to designate gamma radiation.
- d. Since the gamma decay doesn't involve the gain or loss of protons or neutrons, the general equation is slightly different from the other decay equations.



All of the transmutation examples given could be accompanied by gamma emission. Although most nuclear decay reactions do have gamma emissions associated with them, there are some radionuclide species which decay by particulate emission with no gamma emission.

<p>e. Table 2 provides a summary of the characteristics of the various types of radioactive emissions that have been discussed. Table 3 summarizes the various modes of radioactive decay.</p>	<p>See Table 2 - "Types of Radioactive Emissions" and Table 3 - "Modes of Decay"</p>
<p>9. Other Types of Transformations</p>	
<p>a. Internal conversion</p>	
<p>1) This phenomenon occurs when a gamma photon does not escape the electron cloud surrounding the nucleus, but transfers to one of the orbital electrons enough energy to eject it from the atom.</p>	
<p>2) The photon is said to have undergone internal conversion.</p>	
<p>3) The conversion electron is ejected from the atom with kinetic energy equal to the gamma energy minus the binding energy of the orbital electron.</p>	
<p>4) This process usually takes place in the K-shell. There will then follow emission of characteristic X-rays as with electron capture.</p>	<p>In principle, internal conversion is similar to the photoelectric effect (to be discussed in Lesson 1.07).</p>
<p>b. Isomeric transition</p>	
<p>1) Isomeric transition commonly occurs immediately after particle emission; however, the nucleus may remain in an excited state for a measurable period of time before dropping to the ground state at its own characteristic rate.</p>	
<p>2) A nucleus that remains in such an excited state is known as an isomer because it is in a metastable state; that is, it differs in energy and behavior from other nuclei with the same atomic number and mass number.</p>	<p>Generally, the isomer achieves ground state by emitting delayed (usually greater than 10^{-9} seconds) gamma radiation.</p>
<p>3) The metastable or excited state, is usually represented by a small m following the mass number, A, in the standard nuclide notation.</p>	
<p>4) For example, Technetium-99m and Technetium-99 are isomers. $^{99m}_{43}\text{Tc}$ will decay to $^{99}_{43}\text{Tc}$ with the emission of a 140.5 keV gamma. Further</p>	

radioactive decay can still occur from the ground state. In this case, ^{99}Tc decays to ^{99}Ru , which is stable.

D. Decay Phenomena

Objective 1.06.05

1. Each radionuclide, artificial and natural, has its own characteristic pattern of decay. There are several aspects associated with this pattern:

- a. Modes of decay
- b. Types of emissions
- c. Energies of the emissions involved
- d. Rate of decay

2. Mode of Decay

- a. All nuclei of a given radionuclide seeking stability by radioactive decay do so in a specific manner.

^{226}Ra decays by alpha emission which is accompanied by a gamma photon. This represents the only mode of decay open to ^{226}Ra .

- b. There are some radioactive nuclides which may decay with branching, whereby a choice of decay modes exists. In such case, a definite branching ratio exists.

A case in point is the decay of ^{57}Ni , mentioned previously. This isotope of nickel decays 50% by K-capture and 50% by β^+ emission. The branching ratio would be:

$$\frac{\beta^+}{EC} = 1$$

3. Types and energies of Emissions

- a. Not only do various radionuclides disintegrate in a constant manner insofar as the types of emissions are concerned, but the emissions from each nuclide exhibit a distinct energy picture.

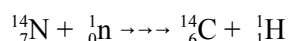
- b. The energies associated with radiations are given in terms of "million electron volts" (MeV).
 - 1) Beta emissions may occur with energies to about 5 MeV
 - 2) Alpha particles to about 10 MeV
 - 3) Gamma photons to about 3 MeV.
 - c. The energy of the particulate radiations is manifested as kinetic energy--the higher the energy the greater the velocity of the particle.
 - d. The velocity of photons is constant (c = speed of light) and energy differences are manifested by varying wavelengths and frequencies.
4. Rate of Decay
- a. The other characteristic aspect associated with decay patterns is the rate of decay, or activity. The disintegrations of radionuclides occur with a regularity characteristic for each particular species.
 - b. Such disintegrations are spontaneous and random. A single radium nucleus, for instance, may disintegrate at once or wait thousands of years before emitting an alpha particle.
 - c. All that can be predicted with any certainty is that half of all the ^{226}Ra nuclei present will disintegrate in 1,622 years. This period is called the half-life of ^{226}Ra .

Half-lives vary greatly for natural occurring radioisotopes; e.g. ^{212}Po , with a half life of 0.298 microseconds and ^{232}Th , with a half-life of over 1.42E10 years.
5. Singly-occurring Natural Radionuclides
- a. Careful measurements show that almost all materials contain traces of radioactivity.
 - b. One might suspect that these traces might be due to contamination with some of the heavy radionuclides belonging to one of the radioactive series described. However, some of the lighter elements are themselves weakly radioactive.

See Table 4 - "Naturally-occurring Radionuclides"

- c. It may have been noted that Carbon-14 was not included as a natural radionuclide in Table 4, even though it has received considerable popular attention in recent years, as naturally-occurring radiocarbon has been found in definite, though small, proportions.

The ^{14}C existing in the atmosphere is being formed continually as a result of nuclear reactions between atmospheric nitrogen and neutrons from cosmic rays. This is shown in the following reaction:



6. Artificial Radioactivity

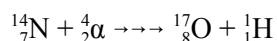
Objective 1.06.06

- a. There are radionuclides which occur as a result of various man-made reactions. These are called artificial radionuclides. The vast majority of radionuclides are produced in this manner.
- b. As implied in the nomenclature, natural and artificial radioactivity differ in origin. There are other distinctions between the two types which will be discussed.
- c. Nevertheless, the nuclei of artificial radionuclides are unstable in much the same manner as their natural counterparts. The intranuclear factors governing decay are also similar for both groups.
- d. A brief account of the discovery of artificial radioactivity will be given before further discussing its similarities and dissimilarities to natural radioactivity.

7. Induced Transmutations

- a. In 1919, Lord Rutherford demonstrated that it was possible to produce artificially a transmutation of elements. The manner in which naturally-occurring radioactive atoms are changed or transmuted by emitting radiation has been discussed.
- b. Lord Rutherford set up and observed a nuclear reaction in reverse, one might say, whereby high-speed charged particles (projectiles) bombarded stable

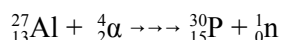
atomic nuclei (target), resulting in a reaction at the nuclear level and inducing a transmutation.



- c. Since the discovery of the transmutation of nitrogen, many hundreds of artificial or induced transmutations have been found. Until 1932, most induced transmutations were performed utilizing naturally occurring alpha emitters as sources of incident particles.
- d. With the development of particle accelerators, other bombarding particles have been successfully used. No attempt will be made here to catalog the many kinds of possible transmutations, nor will any attempt be made to discuss the theory and quantitative data regarding nuclear reactions.

8. Induced Radioactivity

- a. During the first 15 years of experimental work with nuclear reactions, the transmutation products (insofar as could be observed) were not radioactive.
- b. However, the reactions generally were accompanied by the emission of a charged particle and a gamma ray. These emissions are not construed as imparting the property of radioactivity to the target element, since they occur practically instantaneously.
- c. It was determined in 1934 that induced transmutations could produce nuclei which were residually unstable in somewhat the same manner as naturally occurring radionuclides.
- d. Irene Curie and Frederic Joliot reported that certain light elements (boron, magnesium, aluminum), when bombarded with alpha particles, continued to emit radiation for a finite time after bombardment had stopped.
 - 1) The following reaction, involving aluminum bombarded with alpha particles, was the first reported instance of induced or artificial radioactivity:



- 2) The resultant nucleus $^{30}_{15}\text{P}$ was observed to be radioactive, emitting a small charged particle and reaching stability within minutes.
- e. The work of Curie and Joliot stimulated similar experiments throughout the world. As a result, radioactive isotopes of nearly every element in the Periodic Table were produced by bombarding a stable isotope with charged particles, neutrons, or in certain instances photons.
9. Natural vs. Artificial
- a. Heavy radionuclides (natural, and artificial) generally decay by a long series of alpha and beta emissions.
- b. Lighter, artificial radionuclides, such as activation and fission products, usually decay by beta or positron emission or by orbital electron capture.
- c. In contrast to natural radioactivity, lighter artificially-produced radionuclides generally revert to stability in only a few decay steps.
10. Fission Products
- a. Another source of radionuclides is nuclear fission. The nuclear fragments directly resulting from fission invariably have too large a proportion of neutrons to protons for stability, and consequently tend to achieve stability by beta minus emission.
- b. For example, take a thermal fission of ^{235}U :
- $$^{235}_{92}\text{U} + {}^1_0\text{n} \rightarrow {}^{141}_{55}\text{Cs} + {}^{92}_{37}\text{Rb} + 2({}^1_0\text{n})$$
- 1) The n:p ratio for stable Cesium (^{133}Cs) is 1.4:1, whereas the above fission product has a ratio of about 1.6:1.
- 2) The stable ratio for Rubidium (^{85}Rb) is 1.3:1, while the product above has a ratio of about 1.5:1.
- 3) As can be seen, The fission products in the above equation have too many neutrons.
- c. Each fission fragment initiates a radioactive series, called a fission decay chain, involving several successive beta decay transformations.

Over 1,000 unstable nuclear species are listed in the Chart of the Nuclides.

- d. Fission product beta emission, as with other beta emitters, generally is accompanied by gamma emission.

11. Predicting Mode of Decay

- a. Radioactive nuclides tend to decay in a way that results in a daughter nuclide that lies closer to the line of stability.
- b. Nuclides below the line of stability will usually undergo beta-minus decay.
- c. Nuclides above the line of stability will usually undergo positron decay or electron capture.
- d. Nuclides at the upper end of the line of stability will usually undergo alpha decay.
- e. Figure 2 illustrates the type of decay nuclides in different regions will typically undergo.

These are general rules that have many exceptions, especially in the region of heavy nuclides.

See Fig. 2 - "Types of Decay Relative to Line of Stability"

E. Radioactive Families

Objective 1.06.08

- 1. The transmutations associated with naturally-occurring radionuclides frequently yield a daughter which is also radioactive.
- 2. To date, about 70 different naturally occurring radionuclides have been identified, each with its own characteristic pattern of radioactivity.
- 3. Most of these yield radioactive daughters and are now known to be intimately interrelated in radioactive series or families.
- 4. Three Natural Decay Series
 - a. It has been established that most isolated radioactive species with $Z > 82$ belong to one of three independent groups or families.
 - b. Each family starts with a parent radionuclide, decaying or transmuting into a radioactive daughter nuclide, which would again transmute into a daughter

See Fig. 3 - "Natural Decay Series"

nuclide, also radioactive, and so on until stability is attained.

- c. One family starts with Uranium-238 ($^{238}_{92}\text{U}$) and is called the Uranium series.
- d. Another starts with Thorium-232 ($^{232}_{90}\text{Th}$) and is called the Thorium series.
- e. A third starts with Uranium-235 ($^{235}_{92}\text{U}$) and is called the Actinium series.
- f. In each series, there is a "seesawing" in the transmutation chain between decreasing the atomic number by two with α emission and increasing it by one with β^- emission.
- g. Each series has an isotope of Radon [historically known as Radon ($^{222}_{86}\text{Rn}$), Thoron ($^{220}_{86}\text{Rn}$), and Actinon ($^{219}_{86}\text{Rn}$) respectively] as a member of the series. All isotopes of Radon are radioactive and are gases at standard temperature and pressure.
- h. Each series ends in a different stable isotope of Lead ($^{206}_{82}\text{Pb}$, $^{208}_{82}\text{Pb}$, and $^{207}_{82}\text{Pb}$ respectively).
- i. Figure 3 shows the three natural decay series.

5. Artificial Series

- a. There is also a fourth series, the Neptunium series, named after its longest-lived member.
 - Actually, the neptunium series has been artificially produced and no longer occurs in nature, but it is assumed that it did occur in nature at one time and has become extinct because of the relatively short half-lives involved.
- b. The longest-lived radionuclide in the series is $^{237}_{93}\text{Np}$ with a half-life of 2.2E06 years.
- c. Assuming the age of the earth is 2.2E09 years, this would indicate that, from the time of creation, ^{237}Np has undergone 1,000 half-lives decay. The fraction of a radionuclide remaining after 1,000 half-lives would be astronomically small—in the order of 10^{-300} . It is

The historical name of ^{235}U was "Actinouranium." Note its third daughter.

obvious, therefore, why it would be difficult to find traces of neptunium and its descendants in nature.

F. Chart of the Nuclides

Objectives 1.06.09 and 1.06.10

1. General Arrangement

- a. In arranging the nuclides in chart form, the number of neutrons (N) is plotted horizontally on the x-axis against the number of protons (atomic number, Z) on the y-axis
- b. Such a plot at once reveals the continuity in composition in progressing from the lighter to the heavier elements.
- c. The full-size Chart of the Nuclides (poster) is much easier to follow than the Nuclides and Isotopes volume which contains all of the material from the chart in book form.

Post Chart in classroom or provide books for students to use during discussion.

A guide for using the chart is found in the book.

2. Specific Nuclide Representation

- a. Each specific nuclide is represented in the Chart of the Nuclides by a block.
- b. The coloring and labeling of each block specifies certain information concerning the properties of the nuclide.
- c. Values for atomic number (Z) are given along the left side of the grid, and values for number of neutrons (N) are found along the bottom.
- d. A grey block denotes a stable nuclide. A typical example is stable sodium ($^{23}_{11}\text{Na}$).
- e. Unlike sodium, most elements have more than one stable isotope. For example, magnesium (Mg) has three stable isotopes.

Refer students to block for ^{23}Na . Discuss block color and values, such as percent abundance, activation cross-section and atomic mass.

Refer students to blocks for ^{24}Mg , ^{25}Mg and ^{26}Mg . Discuss and compare values.

<p>f. A white block denotes an artificially produced radioactive nuclide. A typical example is $^{59}_{26}\text{Fe}$.</p> <p>g. A white block with a black triangle in the lower right hand corner denotes an artificially produced radionuclide resulting from slow neutron fission (fission product).</p> <p>h. A grey block with a black bar across the top denotes a long-lived, naturally- occurring radioactive isotope. $^{238}_{92}\text{U}$ is a good example.</p>	<p>Refer students to block for ^{59}Fe. Discuss half-life, emissions and energies, etc.</p> <p>Refer students to block for ^{90}Sr. Discuss values.</p> <p>Refer students to block for ^{238}U. Discuss block colors and values.</p>
<p>3. Depicting Nuclear Processes</p> <p>a. As a result of decay, radionuclides shift from block to block within the Chart of the Nuclides. The diagram shows the relative locations of the products of various nuclear processes.</p> <p>b. As can be seen, the relative locations (displacements) of the primary modes of decay are:</p> <p>1) Alpha (α):</p> <p style="padding-left: 40px;">down 2, left 2 ($\downarrow \downarrow, \leftarrow \leftarrow$)</p> <p>2) Beta ($\beta^-$):</p> <p style="padding-left: 40px;">up 1, left 1 ($\uparrow \leftarrow$)</p> <p>3) Positron (β^+)/EC:</p> <p style="padding-left: 40px;">down 1, right 1 ($\downarrow \rightarrow$)</p> <p>c. Displacements can also occur as a result of nuclear reactions brought about through bombarding given nuclides with various nuclear particles or gamma photons.</p>	<p>Refer students to diagram in Study Guide</p> <p>These changes are depicted in the "Guide for using the Chart of the Nuclides."</p>
<p>4. Chart of the Nuclides Summary</p> <p>a. The Chart of the Nuclides provides considerable information about the behavior of nuclides. There is continuity in composition of the nuclides.</p>	

- b. A line drawn through the stable nuclides forms a rather smooth curve extending from the lower left to the upper right corner of the Chart of the Nuclides.
- c. Nuclides below this line are characterized by having an excess of neutrons and will, in general, be beta particle emitters.
- d. Nuclides above this line are characterized by having an excess of protons and will, in general, decay by positron emission or electron capture.
- e. Nuclides lying beyond the line of stability will, in general, demonstrate a tendency to seesaw between alpha decay and beta decay.
- f. All nuclides, if followed through their various decay schemes will eventually end in a gray box (stable isotope).
- g. The Chart presents in compact style much valuable information concerning the properties of the nuclides. These data include for:
 - 1) Stable nuclides
 - a) Relative abundance
 - b) Cross section for activation
 - 2) Radioactive nuclides
 - a) Types of emissions
 - b) Energies of emissions
 - c) Half-life

G. Units of Activity

Objective 1.06.11

1. The rate of decay of a radioactive substance constitutes the quantity of radioactivity, or activity, in that substance.
 - a. The definition of activity refers to the number of transformations (disintegrations) per unit time.
 - b. Since the fundamental unit of time is the second, the quantity activity is measured in disintegrations per second, or dps. Since the second is a very short time

period in which to make a measurement, activity is measured in units of disintegrations per minutes, or dpm.

- c. The SI unit of activity is the becquerel, while the historical unit is the curie. Each will be discussed below.

2. The Curie

- a. Before the large-scale production of artificial radioisotopes, radium had become a standard of comparison for radioactivity measurements. Originally, the unit curie applied only to radium.
 - 1) Named for Marie Curie, it was based on the disintegrations per second (dps) occurring in the quantity of radon gas in equilibrium with one gram of radium.
 - 2) If permitted to attain this equilibrium, one gram of radium will produce about 0.66 mm³ of radon.
 - 3) In this quantity of radon, about 37 billion atoms disintegrate each second.
- b. In 1930, the International Radium Standard Commission extended the definition to include that quantity of any radioactive decay product of radium which underwent the same number of dps as one gram of radium.
 - It avoided specifying the figure exactly, so for some years the exact value of the curie varied with each successive refinement in the measurement of the decay constant or the atomic weight of radium.
- c. In 1950, the International Joint Commission on Standards, Units, and Constants of Radioactivity redefined the curie by accepting 37 billion dps as a curie of radioactivity regardless of its source or characteristics.
- d. Current regulations define the curie (Ci) as 3.7E10 disintegrations per second (2.22E12 dpm).

Objective 1.06.11 a.

<p>e. Since the curie represents a very large amount of activity, often smaller, and more convenient subunits are used.</p>	<p>See Table 5 - "Curie Subunits"</p>
<p>3. The Becquerel</p>	<p>Objective 1.06.11 b.</p>
<p>a. The SI derived unit of activity is the becquerel (Bq) and is that quantity of radioactive material in which one atom is transformed per second or undergoes one disintegration per second (1 dps).</p>	<p>1 dps = 1 Bq</p>
<p>b. Since the becquerel is a rather small unit, metric prefixes are often applied to aid in designating larger amounts of activity.</p>	<p>See Table 6 - "Becquerel Superunits"</p>
<p>c. The relationship between the becquerel and curie is:</p> <p>1) $1\text{Bq} = 1\text{ dps} = 2.7\text{E-}11\text{ Ci}$</p> <p>2) $1\text{ Ci} = 3.7\text{E}10\text{ dps} = 3.7\text{E}10\text{ Bq}$</p>	
<p>4. Using unit analysis and conversion, activity measurements given in dps, dpm or curies can be converted to becquerels.</p>	
<p>H. Specific Activity</p>	<p>Objective 1.06.12</p>
<p>1. Specific activity is defined as the activity per unit mass of a radioactive substance.</p>	
<p>2. Reported in units such as curies per gram (Ci/g) or becquerels per kilogram (Bq/kg).</p>	
<p>3. Recall that the curie originated from the number of emanations from one gram of radium every second.</p>	
<p>4. Thus, the activity of one gram of radium is equivalent to one curie. This means that the specific activity of radium would be 1 Ci/g.</p>	
<p>5. It is important, however, to note that when applied to radionuclides other than radium, the unit curie does not make apparent what mass of the material is required.</p>	
<p>6. Since one curie of activity is 37 billion dps, the mass of the material required to produce this number of dps will be a function of the decay rate of the atoms of the material (i.e., the disintegration constant) and of the number of atoms of the material per gram (i.e., gram atomic mass [weight]).</p>	

For example, a curie of pure ^{60}Co ($T_{1/2} = 5.27$ years) would have a mass less than 0.9 milligrams, whereas a curie of natural ^{238}U ($T_{1/2} = 4.5\text{E}9$ years) would require over two metric tons of the metal.

7. Obviously, the shorter the half-life of a radionuclide, the greater its specific activity.

I. The Radioactive Decay Law

1. The activity of any sample of radioactive material decreases or decays at a fixed rate which is a characteristic of that particular radionuclide.
2. No known physical or chemical agents (such as temperature, pressure, dissolution, or combination) may be made to influence this rate.
3. The rate may be characterized by observing the fraction of activity that remains after successive time intervals.
4. For convenience we choose a fraction that is easy to work with, one-half ($1/2$).
5. In using this fraction we can observe the decay of a radionuclide with the passing of time. We can observe how long it takes for the activity to be reduced to one half of the activity.
6. This time that is required for the activity present to be reduced to one-half we call the half-life.
7. If successive half-lives are observed, we can see a reduction each time by a fraction of one-half, and the effect will be cumulative.
 - a. One half-life reduces to $(1/2)^1$
 - b. Two half-lives reduces to $1/2 \times 1/2 = (1/2)^2$ or $1/4$
 - c. Three half-lives will reduce to $1/2 \times 1/2 \times 1/2 = (1/2)^3$ or $1/8$
8. In the general case the fraction of activity remaining after any number of half lives will be $(1/2)^n$, where n is the number of half-lives that have elapsed.
9. To put it still another way, the reduction in activity occurs at an exponential rate, which we have expressed as the power of $1/2$.

Objective 1.06.13

10. In Figure 4 it can be seen that as time passes, radioactive decay occurs at an exponential rate.
- In using the half-life for our time value, we express this exponential function as $(\frac{1}{2})^n$.
 - Beginning at the instant chosen as the starting point we have 100% of the activity, since no time has elapsed, and the number of half-lives is zero ($n = 0$).
 - If we use t to represent time, at this point, then, $t = 0$.
11. If we let $T_{1/2}$ represent the half-life, then, after one half-life, $t = T_{1/2}$, and $n = 1$. This demonstrates that n represents the ratio of time versus the half-life.
12. Mathematically, this is expressed as:

$$n = \frac{t}{T_{1/2}}$$

where:

$$\begin{aligned} n &= \text{number of half-lives} \\ t &= \text{time elapsed} \\ T_{1/2} &= \text{half-life} \end{aligned}$$

13. Obviously, the units of t must be the same as the time units of $T_{1/2}$ in order to determine the value of n .
- For example, if the half-life of a certain radionuclide is 10 hours, and we allow 4 hours to elapse, the number of half-lives would be $4/10 = 0.4$, or 0.4 half-lives.
 - The fraction remaining at that instant where $t = 4$ hours would be:

$$\left(\frac{1}{2}\right)^{\frac{4}{10}} = \left(\frac{1}{2}\right)^{0.4} = 0.7578$$

14. The activity at the instant where $t = 0$ is the initial or original activity, represented as A_0 .
15. The activity at any time t after 0 we will denote as A_t .

See Fig. 4 - "Radioactive Decay (Linear Scale)"

16. The value of A_t at any time t will be the fraction remaining times A_0 . The fraction remaining is determined from the number of half-lives that have passed.

A useful "rule of thumb" to remember is that seven half-lives will reduce any activity to less than 1 percent of its original value.

17. Using a proportion we can see the relationship between the two activities:

$$\frac{A_0}{A_t} = \frac{1}{(\frac{1}{2})^n}$$

18. By cross-multiplying we obtain the equation for determining the remaining activity:

$$A_t = A_0(\frac{1}{2})^n$$

For example, if the initial activity of the radionuclide mentioned above was 52 μCi , then the activity after 4 hours would be:

$$\begin{aligned} A_t &= 52 \mu\text{Ci} \left(\frac{1}{2} \right)^{\frac{4}{10}} \\ A_t &= 52 (0.7578) \\ A_t &= 39.4 \mu\text{Ci} \end{aligned}$$

19. Remember that we stated earlier that radioactive decay is an exponential process. Recall also that a logarithm is, by definition, an exponent.

20. If we were to plot the activity on a logarithmic scale against the time on a linear scale, the resulting curve should be a straight line.

See Fig. 5 - "Radioactive Decay (Semi-log Scale)"

21. This graph shows us that the rate of decay does in fact occur at a constant rate.

22. As time elapses from the starting instant, the activity is reduced thereafter at the constant rate of disintegration for the particular radionuclide involved, which we represent by the Greek letter λ (pronounced "lambda").

23. In FIGURE 5 the reduction of activity is now a logarithmic (exponential) function of $(\frac{1}{2})^n$.

24. Since n is the ratio of t versus $T_{1/2}$, the fraction remaining after time t will be less than 1, resulting in a negative natural-logarithmic value ($\ln 1/2 = -\ln 2 = -0.693$).

Using calculus, the natural logarithm (ln) resulted from the integration of the first equation devised by Rutherford.

25. The fraction remaining will be a function of the decay constant (λ) and the time (t).
26. If we then relate the decay constant to the half-life, λ will be a composite of the natural log of 2 and the half-life.
27. Since the process leads to a decrease in activity, the exponent will be represented by $-\lambda t$.
28. Therefore, the decay constant itself will represent:

$$\lambda = \frac{\ln 2}{T_{1/2}} = \frac{0.693}{T_{1/2}}$$

29. Thus, the decay constant is the fraction that disintegrates per unit time (reciprocal time).
- If, for example, the half-life is in seconds, λ will be in sec^{-1} .
30. The equation for activity using the decay constant will be:

Objective 1.06.14

$$A_t = A_0 e^{-\lambda t}$$

- Note that in this equation the base of the natural log is raised to a power which includes the $-\ln 2$.
 - The result of this equation is exactly the same at that which results from the equation using $(1/2)^n$.
 - It is simply a different way of expressing the decrease in activity with the passage of time as a result of radioactive decay.
31. Using the data in the prior example, the equation would be:

$$A_t = 52 e^{\left(\frac{-\ln 2}{10}\right)4}$$

$$A_t = 52 e^{-0.277}$$

$$A_t = 52 (0.7578)$$

$$A_t = 39.4 \mu\text{Ci}$$

32. Example: Given 10 mCi of ^{32}P , which has a half-life of 14.2 days, find the quantity remaining after 60 days.

$$A_t = 10e^{\left(\frac{-\ln 2}{14.2}\right)60}$$

$$A_t = 10e^{-2.93}$$

$$A_t = 10(0.0534)$$

$$A_t = 0.534 \text{ mCi}$$

Work example problem with students.

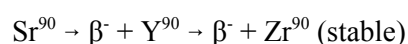
33. By algebraic manipulation other variables in this equation can be solved for if the other values are known.

- One example would be calculating the original activity based on the current activity, decay constant and elapsed time.

Have students work practice problems in Study Guide.

J. Series Decay

1. Concerns the mathematical relationship of quantities of activity present when two or more radionuclides exist in a decay chain.
2. Examples of a decay chain are the natural decay series, or a two-step fission product decay series such as:



3. The relationship between three or more radionuclides is described by H. Bateman. The solution, while straight forward, is quite involved. A two-step relationship (parent-daughter) can be readily derived and is reasonably easy to work with.

K. Parent-daughter Relationships

1. In a radioactive decay series, the decay of the parent nuclide produces a daughter product and radiation is emitted.
2. The daughter nuclide also produces radioactivity when it decays, as does each successive daughter in the chain until stability is reached, resulting in total collective activity.

<ol style="list-style-type: none"> 3. The activity contributed from the parent versus the daughters will vary depending on the half-life of the parent and the half-lives of the daughters. 4. When the number of atoms being produced is the same as the number of atoms that are decaying, a state of equilibrium is said to exist. 5. There are several types of equilibrium, depending on how the half-life of the daughter compares to the half-life of the parent. <ol style="list-style-type: none"> a. Secular Equilibrium <ol style="list-style-type: none"> 1) In secular equilibrium the half-life of the parent is very much longer than the half-life of the daughter. When in equilibrium, the activity of the daughter is equal to the activity of the parent. 2) Initially, the majority of the activity will be contributed by the parent. 3) As more and more of the parent nuclide decays, the amount of activity contributed by the daughter will increase. b. Transient Equilibrium <ol style="list-style-type: none"> 1) In transient equilibrium the half-life of the parent is longer than that of the daughter, but not very long. 2) In a freshly purified parent fraction, the daughter activity builds up, then decays with the same rate of decay as the parent. c. No Equilibrium - When the half-life of the parent is shorter than that of the daughter, the two never reach a state of equilibrium. 	
<p>L. Radiation Dosimetry Terminology</p> <ol style="list-style-type: none"> 1. During the early days of radiological experience there was no precise unit of radiation dose that was suitable either for radiation protection or for radiation therapy. 	<p>See Fig. 6 - "No Equilibrium"</p> <p>Objectives 1.06.15 and 1.06.16</p>

<ul style="list-style-type: none"> a. For example, one early unit devised was the "skin erythema unit," where allowable dose was the amount required to produce skin reddening. b. Because of the great energy dependence of these various units, as well as other inherent defects, none of these was useful for radiobiological studies or for radiation protection. c. Furthermore, since the fraction of the energy in a radiation field that is absorbed by the body is energy dependent, it is necessary to distinguish between radiation exposure and absorbed dose. 	
2. Exposure (X)	
<ul style="list-style-type: none"> a. Exposure is a measure of the ability of photons (X and gamma) to produce ionization in air. 	Objective 1.06.15 a.
<ul style="list-style-type: none"> b. Traditionally, the unit of exposure is the roentgen (R). The unit is defined as the sum of charge per unit mass of air; that is: 1 roentgen = 2.58×10^{-4} C/kg of air 	Objective 1.06.16 a. The roentgen was originally defined as the quantity of X or gamma radiation that will produce ions carrying 1.0 electrostatic unit (esu) of electrical charge in 1 cubic centimeter of dry air under standard conditions.
<ul style="list-style-type: none"> c. There is no SI unit defined for exposure. This was done intentionally to discourage further use of the quantity. 	
<ul style="list-style-type: none"> d. The definition of the roentgen places severe limitations on the interpretation of radiation measurements since it describes only the amount of ionization caused by x-ray or gamma radiation ($E < 3$ MeV) in air. 	
<ul style="list-style-type: none"> e. Another unit must be used to describe the amount of ionization caused by any radiation in any material. 	
3. Absorbed Dose (D)	
<ul style="list-style-type: none"> a. Units of dose measure the amount of radiation energy absorbed or deposited per unit of mass. 	Objective 1.06.15 b.

- b. The "energy deposited" by radiation is an expression for the "amount of ionization caused" and both expressions mean the same thing.
- c. For example, as a charged particle passes through air, it creates ion pairs. The creation of each of these pairs requires about 33.9 eV.
- d. The radiation, therefore, gives up this amount of energy to the air each time it creates an ion pair; in other words, it deposits energy in the air.
- e. The Rad

- 1) The old (CGS) unit of absorbed dose is the rad, which is an acronym for Radiation Absorbed Dose.
- 2) The unit rad can be applied to all types of radiation and is defined as the deposition by any radiation of 100 ergs of energy in one gram of any material.

f. The Gray

- 1) The SI Derived unit of absorbed dose is the gray (Gy), equivalent to the deposition of one joule of energy per kilogram (1 J/kg).
- 2) The relationship between the gray and the rad is that 1 Gy = 100 rad:

$$1 \text{ Gy} = \frac{1 \text{ J}}{\text{kg}} \times \frac{1 \text{E7 ergs}}{1 \text{ J}} \times \frac{1 \text{ kg}}{1 \text{E3 g}} \times \frac{1 \text{ rad}}{100 \text{ ergs/g}} = 100 \text{ rad}$$

g

Although the rad and gray are measures of ionization produced, they do not give any information about the biological effects of the radiation that is absorbed.

- h. It is meaningful to emphasize that the energy deposited by the radiation (as a result of the

Objective 1.06.16 b.

For simplicity purposes, 1 rad of photons is usually considered to be equivalent to 1 R. The actual physical relationship is such that an exposure of 1 R would produce an absorbed dose of 0.87 air rads. This means that 1 R = 87 ergs/g.

ionization) is the quantity which is actually measured in rad units.

- i. Thus, the amount of ionization produced in the detector of a radiation detection instrument can be related to the energy absorbed and expressed by the instrument meter in the unit rad or rad/hr.

4. Quality Factor (Q)

- a. A quality factor is used to relate the absorbed dose of various kinds of radiation to the biological damage caused to the exposed tissue.
- b. A quality factor is necessary to relate the effects of radiation because the same amounts absorbed energy per kilogram of tissue of different kinds of radiation cause different degrees of damage.
- c. The quality factor converts the absorbed dose to a unit of dose equivalence (discussed below) to a common scale that can be added with and compared to damage caused by any kind of radiation.
- d. The quality factor is a conversion factor used to derive the dose equivalent from the absorbed dose, expressed as:

$$H = DQ$$

where:

H = dose equivalent

D = absorbed dose

Q = quality factor

- e. There is a quality factor associated with each specific type and energy of radiation. By knowing what type and energy of radiation is present, we can determine the quality factor and relate the absorbed dose to the dose equivalent.
- f. A high quality factor indicates that type of radiation has a greater biological risk or greater effect than radiation with a lower quality factor for the same absorbed dose.

Objective 1.06.15 c.

See Table 7 - "Quality Factors"

- g. For example an absorbed dose of 100 millirad thermal neutron would be converted to dose equivalent as follows:

$$100 \text{ mrad (n)} \times 3 = 300 \text{ mrem}$$

- h. The quality factor can also be applied to an absorbed-dose rate (rad/hr) in order to obtain dose-equivalent rate (rem/hr).

5. Dose Equivalent (H)

- a. A measurement of the dose equivalent is calculated as the absorbed dose multiplied by the quality factor, which relates the relative risk from the type of radiation absorbed to the risk from the same dose of X or gamma radiation.

Objective 1.06.15 d.

b. The Rem

- 1) The old unit of dose equivalent is the rem, which is an acronym for Roentgen Equivalent Man.
- 2) The rem was the quantity of ionizing radiation whose biological effect (in man) is equal to that produced by 1 roentgen of x-rays or gamma radiation.
- 3) The dose equivalent in rem is numerically equal to the absorbed dose in rad multiplied by the quality factor:

Objective 1.06.16 c.

$$\text{rem} = \text{rad} \times Q$$

c. The Sievert

- 1) The SI Derived unit of dose equivalence is the sievert (Sv).
- 2) The dose equivalent in sieverts is equal to the absorbed dose in grays multiplied by the quality factor:

$$\text{sievert} = \text{gray} \times Q$$

- 3) Since, one gray is equal to 100 rad, it follows that for $Q = 1$:

$$1 \text{ Sv} = 100 \text{ rem}$$

- d. It should be emphasized that the relative risk from one rem dose equivalent from neutrons is the same as the risk from one rem dose equivalent from gamma or any other radiation.
- e. Use of dose equivalent units for recording personnel radiation exposure permits us to add exposures from various types of radiation and get a total dose equivalent which is proportional to the risk.
- f. Table 8 provides a summary of these dosimetry units and their associated values.

See Table 8 - "Dosimetry Terminology Summary"

III. SUMMARY

A. Review major topics

- 1. Neutron to proton ratio
- 2. Radioactivity and radioactive decay
- 3. Radiation characteristics
- 4. Decay modes
- 5. Natural/artificial radioactivity
- 6. Fission product stability
- 7. Chart of the nuclides
- 8. Units of activity
- 9. Activity calculation
- 10. Measurement terminology

B. Review learning objectives

IV. EVALUATION

Evaluation should consist of a written examination comprised of multiple choice questions. 80% should be the minimum passing criteria for the examination.

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